

Robotics and Manipulators for Reactor Pressure Vessel Head Inspection

S.W. Glass¹, M.Sloman², F.Klahn³, G.Guse⁴, E. Brau⁵

¹⁻³AREVA NDE Solutions, Lynchburg Virginia, USA

⁴AREVA NDE Solutions, Erlangen Germany, ⁵Cadarache France

¹Bill.Glass@AREVA.com; ²Mark.Sloman@AREVA.com; ³Frank.Klahn@AREVA.com;

⁴Gunter.Guse@intelligeNDT.de.; ⁵Emmanuel.Brau@AREVA.com

Abstract

The complex geometry of reactor pressure vessel (RPV) heads presents one of the greatest access challenges for inspection and repair within a typical pressurized water reactor system. Initially most of the Pressurized Water Reactor (PWR) fleet heads were manufactured with Inconel 600 nozzles and with A-52 weld material that are now known to be susceptible to primary water stress corrosion cracking. Most of these heads have been replaced with less susceptible material but the RPV head component has a demonstrated history of cracks and in some cases, significant leaks. This has prompted regulatory mandated periodic inspection and repair if necessary. Subtle differences in the global inspection requirements and in the head geometries also require different inspection tooling for different global regions and designs.

AREVA NDE Solutions has been involved in head inspection and repair since the earliest crack indications and has developed an extensive array of robotics and manipulators to address these concerns.[2] This paper describes the main manipulators and inspection tools specifically focusing on recent design evolutions including:

- NUMAN for under-head inspection and repair tool positioning.
- Advances to ultrasonic blade tools and probes for nozzle and nozzle-weld interface inspection in nozzles with thermal sleeve.
- Rotating UT and ET tools for nozzles without thermal sleeves.
- An eddy-current J-weld inspection manipulator (recently improved).
- Clamp-on scanner for EPR nozzle butt-welds.
- An eddy-current blade tool with integrated manipulator for AREVA's larger EPR nozzles.
- Head weld seam manipulators for automated head-seam inspection.

Keywords

Reactor-head; Inspection; Manipulator; Robot; J-Weld and Blade-UT

Introduction

Reactor Pressure Vessel (RPV) Head designs vary among the many vendors and many types of reactors but most Pressurized Water Reactors (PWRs) share a number of similarities. The shell and flange may be fabricated from a single forging or as two or more welded pieces but generally its shape is a half-spherical shell with a heavy bolt flange (Fig. 1). The bolt flange has a flat seal surface with two seal ring grooves. The shell has from 36 to 70 penetrations with welded or threaded nozzles that hold the Control Rod Drive Mechanisms (CRDMs) (Fig. 2). Initially most of the Pressurized Water Reactor (PWR) fleet heads were manufactured with Inconel 600 nozzles and with A-52 weld material. These materials are now known to be susceptible to Primary Water Stress Corrosion Cracking (PWSCC). Such cracking was initially observed in the early 1990s. In some cases, cracking, and erosion have resulted in leaks and serious compromises of the primary systems' structural safety margins [1]. Most of these heads have been replaced with less susceptible material but the

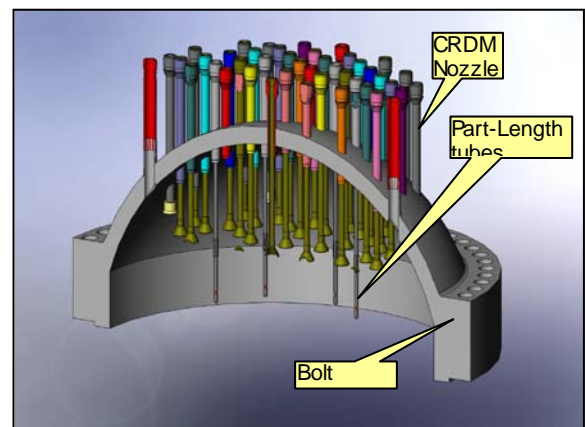


FIG. 1 RPV HEAD CROSS-SECTION SHOWS NOZZLE/DOME INTERSECTION COMPLEX GEOMETRY

RPV head component has a demonstrated history of cracks and in some cases significant leaks. This has prompted regulatory mandated periodic inspection and repair, if necessary. Subtle differences in the global inspection requirements and in the head geometries also require different inspection tooling for different global regions and designs.

Heads are removed from the vessel during refueling and placed on the head-stand within the reactor containment building. The head-stand shields workers from radiation on the outside of the head, however, typical radiation fields beneath the dome are from 10 to 100mR/hour [0.1 to 1mSv/hour] (max allowable radiation worker annual dose is <2000-5000mR [20-50mSv/hour]) so personnel access is very limited or not allowed at all beneath the dome. Usually the standard head-stands place the nozzles and flange-face close to the floor so lifting spacers are required to improve robot access if the heads are to be inspected or repaired.

AREVA NDE Solutions has been involved in head inspection and repair since the earliest crack indications and has developed an extensive array of robotics and manipulators to address these concerns. Selection of the appropriate manipulator depends on the inspection and/or repair application plus the head and head-stand configuration. This paper describes the main manipulators specifically focusing on recent design evolutions including:

- NUMAN for under-head inspection and repair tool positioning.
- Advancements to UT blade probes for nozzle inspection in nozzles with thermal sleeves.
- Rotating UT and ET tools for nozzles without thermal sleeves.
- An eddy-current blade tool and integral manipulator for AREVA's larger EPR nozzles.
- Clamp-on scanner for EPR nozzle but-welds.
- An eddy-current J-weld inspection manipulator (recently improved).
- A lightweight 6-DOF robot for head-weld-seam inspection.

Under-Head Manipulators

ARAMIS 4-DOF ROBOT:

Under-head manipulators have undergone several

design evolutions. The first generation of under-head manipulator was based on AREVA's steam-generator robot ARAMIS. This 4-degree-of-freedom (4-DOF) robot mounts to a tripod platform and can support a number of tools, including rotating and blade-probe UT and ET plus various repair tools. The robot must first calibrate its location on two known nozzles. Thereafter, the location of each nozzle beneath the dome is registered as the inspection or repair activity progresses. Most of the tools can be loaded onto the arm as it reaches out through the gap in the head-stand. This configuration has been qualified with a number of utilities and is still used today. The principal concerns with this robot configuration are stability of the robot platform. The robot arm is somewhat flexible so all tools must latch to the head for stability.

NUWMAN Under-head Manipulator

In the US, inspection and repair activity was very active in the mid and late 90s. The early US utility and regulatory approach was more for inspection programs, coupled with repair of the nozzles, if necessary rather than complete replacement of the heads. In order to speed the inspection and provide a more stable platform for some tools, a new manipulator was developed – NUMAN. This system provides three controlled degrees of freedom plus a tilt function to allow the tool to reach out through the head-stand for tool-change, probe-change, or limited tool maintenance. As with the ARAMIS manipulator, the control system offers full calibration and registration of the manipulator with the nozzle. In addition, the NUMAN control system manages path planning to avoid collisions with nozzles or part-length obstacles extending into the potential manipulator motion path, 3-D simulated views of both

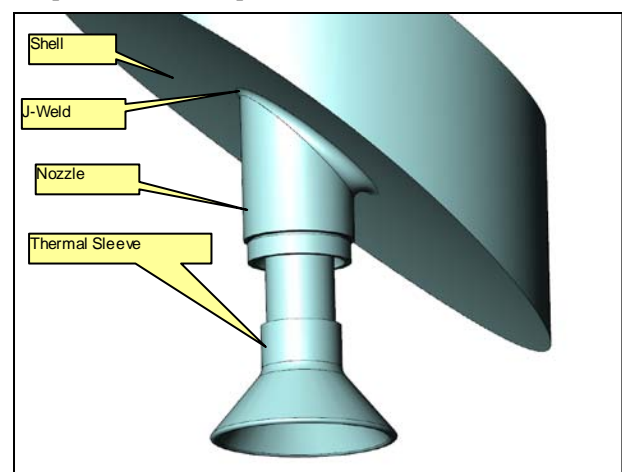


FIG. 2 CRDM NOZZLE PENETRATION WITH THERMAL SLEEVE PROTRUDING

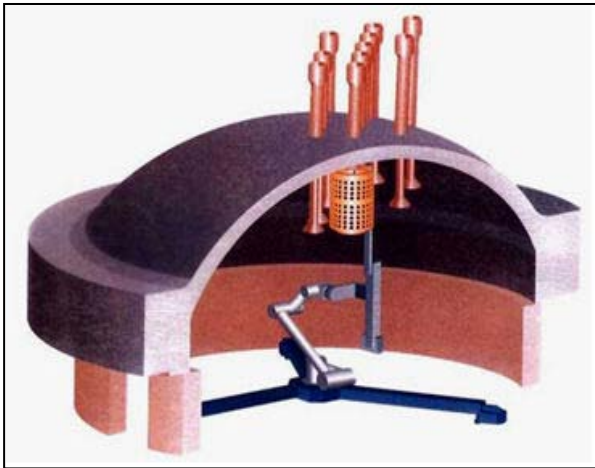


FIG. 3 ARAMIS WITH BLADE TOOL

the manipulator within the head-stand and simulated camera views to be matched with actual cameras on the manipulator. Tools for this manipulator include rotating UT & ET probes, UT blade probes and an

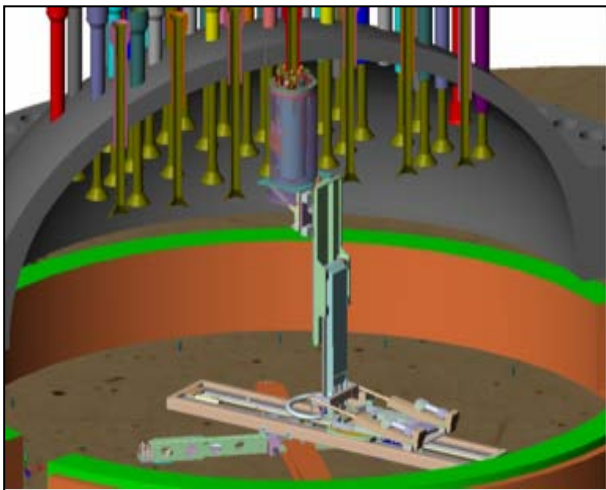


FIG. 4 NUMAN 4-DOF UNDER-HEAD MANIPULATOR

array of repair tools to repair or replace cracked or damaged nozzles.

German Manipulators Evolving to EPR Manipulators

Although inspection capability is important in Europe, through the 90s and even today, there has been far less focus on repair. In France and most of the rest of Europe with traditional PWR head designs, the utilities decided to replace the I-600 nozzles with I-690 nozzles that are thought to be much less susceptible to PWSCC. In Germany, many of the nozzles were screwed into the head rather than welded, thereby, further lessening the chance of cracking within the susceptible weld region. Thus, simpler manipulators can be used focusing primarily on ET or UT surface

examinations to assure the integrity of the system. This same philosophy has extended to AREVA's new larger EPR head design that requires a longer reach into the nozzle to completely cover the regions of interest. For the EPR, the traditional European R-Theta-Z approach, coupled with a tilting tool-head and a centering camera are employed to access the nozzle from the head-stand area. A rotating probe is then pushed through and beyond the thermal sleeve to inspect nozzle welds more than two meters above the shell. In this application, a traditional Steam-Generator probe driver is integrated into the manipulator.

Nozzle Inspection

Rotating Probe Inspection

Rotating probe inspection is performed on nozzles typically 75-100mm in diameter) without thermal sleeves or on the part-length nozzles (typically

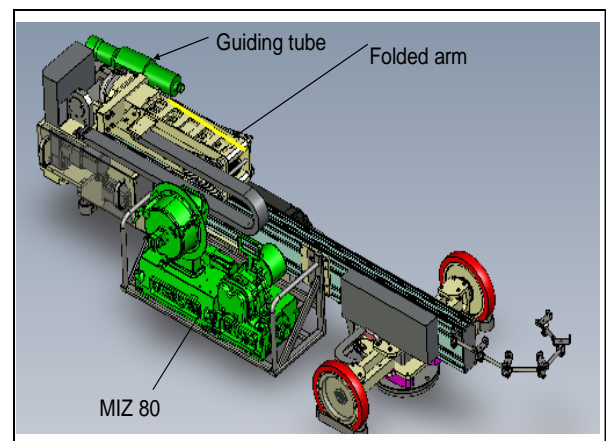


FIG. 5 R-THETA-Z TILTING 4-DOF MANIPULATOR WITH INTEGRAL ET SYSTEM

25-50mm in diameter). Inspections may be based on UT or ET. ET inspections check the first few millimeters of material for surface cracks. Flaws originating from the opposite surface or deeper than a few millimetres will not be detected by ET. UT requires water couplant to transmit the UT signals into the nozzle material and to receive any reflections indicative of flaws or areas of concern.

The probe is inserted into the nozzle and then scanned over the area of interest in a helical pattern. Signals are transmitted through multi-channel slip-rings to allowing a continuous helical scan of the region of interest. Data quality is checked and verified before allowing the manipulator to move to the next nozzle

location. Detailed analysis may be delayed by several hours depending on the specific site schedule and setup logistics.



FIG. 6 ROTATING PROBE CAN SUPPORT EITHER UT OR ET SENSORS



FIG. 7 CIRCUMFERENTIAL (CENTER), AXIAL (RIGHT) AND DUAL (LEFT) BLADE UT PROBES

Blade-Probes

The blade-probes are inserted into the 2-5mm gap between the thermal sleeve and the nozzle. Springs react against the thermal sleeve to press the sensors in close contact with the nozzle ID. For the UT sensors (Fig. 7), water is injected through the blade to complete the sensor coupling to the nozzle. Raster scans are then performed to scan the full area of interest near the nozzle-to-shell weld. For ET sensors, the primary criterion is to have close coupling between the sensing coil and the inspection surface (Fig. 8). Insertion and scanning principals are the same as for the UT probes except that there is no need for water coupling.



FIG. 8 ET BLADE PROBE

In the US, the primary inspection focus has always been volumetric UT of the nozzle and interface between the nozzle and the J-weld. Since the initial discovery of cracks in the early 90s, qualifications had been based on vendor demonstrations at the Electric Power Research Institute (EPRI) but were not subject to the rigors of a blind Performance Demonstration Initiative (PDI). AREVA and others had performed such demonstrations as qualification justifications for their examinations. As with most vendors, the examination consisted of a single circumferential looking blade probe primarily focused on axial cracks followed, if necessary, by an axial looking blade probe primarily looking for circumferential cracks. Since real PWSCC cracks are irregular in nature and will likely present a reflection with either orientation, screening with either direction was adequate to detect flaws.

The US NRC issued a notice [3] that all head inspection vendors must qualify or re-qualify their head inspection methods in accordance with blind PDI protocols by 2010. Although real PWSCC presents irregular facets that follow grain boundaries and can be detected with either axial or circumferential probes, the new blind mock-ups were squeezed EDM cuts that were primarily axial or circumferential and could be only detected and sized with the correctly oriented sensors. This prompted AREVA to upgrade its head inspection program by combining both axial and circumferential probes into a single blade sensor. Rather than requiring two scans of the nozzle, the complete nozzle inspection is performed in a single pass. This new qualification was passed in 2010.

Epr Upper Nozzle Weld Ut Scanner

AREVA's EPR Generation 3 Reactor also has some nozzle welds that cannot be reached with traditional blade or rotating probes from inside the nozzle. A special clam-shell clamp-on UT scanner has been developed to inspect these welds. The clam-shell scanner is lowered by a two-rope winch positioned by a two axis crane installed on the head assembly's lifting equipment. The clam-shell assembly is then remotely closed to clamp to the nozzle at the correct elevation (Fig. 9). OD UT sensors are then scanned circumferentially and axially as in a traditional pipe scanner to inspect the weld volume of interest.

J-Weld Inspection

Periodic in-service J-weld inspection is not required by most regulators; however, most new heads do require a baseline J-weld inspection. If cracks are suspected from visual examinations or potential leak indications, a supplemental or for-information in-service J-weld examination may be required to better understand the flaw mechanism. Cracks or indications that are determined to be only a few millimeters may be ground out. If the crack extends deep into the weld, nozzle or shell, more aggressive repairs may be required.

A new J-weld ET tool was developed in 2011 to improve performance and signal quality over an earlier simpler tool. The new J-weld ET tool is delivered to the nozzle from NEWMAN or one of the other under-head manipulators. The tool has a wide open center area to pass by the thermal sleeve funnel. After clamping onto the nozzle, the tool has three controlled degrees of freedom to scan circumferentially, axially and radially. This allows complete and controlled coverage of the J-weld surface area and heat-affected zone. Precise tracking of the J-weld surface is aided by the touch profiling sensor that establishes the exact weld geometry, thereby, allowing the ET sensors to be driven exactly to the target inspection surface. Passive compliance and gimbaling within the tool plus the compliant surface of the ET array maintain the desired surface contact. This was successfully deployed in 2012 with good NDE performance and minimal accumulated personnel dose.

Shell-Weld & Ligament Inspection

Automated shell-welds and ligament inspections are primarily required by the KTA and Scandinavian codes. Traditionally, this examination has been



FIG. 9 CLAMP-ON OD UT SCANNER FOR EPR NOZZLES

performed by dedicated custom tracks that fit exactly to the head and weld geometry. Advances in the lightweight 6-DOF arm makes alternative approaches possible. Instead of fabricating specific 2-DOF scanning tracks, a 6-DOF programmable arm can be setup to perform the scans. For the head activity, the arm is mounted to a circumferential ring allowing maximal radial reach into the nozzle forest. This system was successfully deployed during the summer of 2011.

Conclusion

Head inspection and repair requires a wide range of manipulators and tools. The right level of universality flexibility, capability, and cost are determined by the specific geometry of the head and head stand, by the required inspections in accordance with national regulatory codes and customer preferences, plus

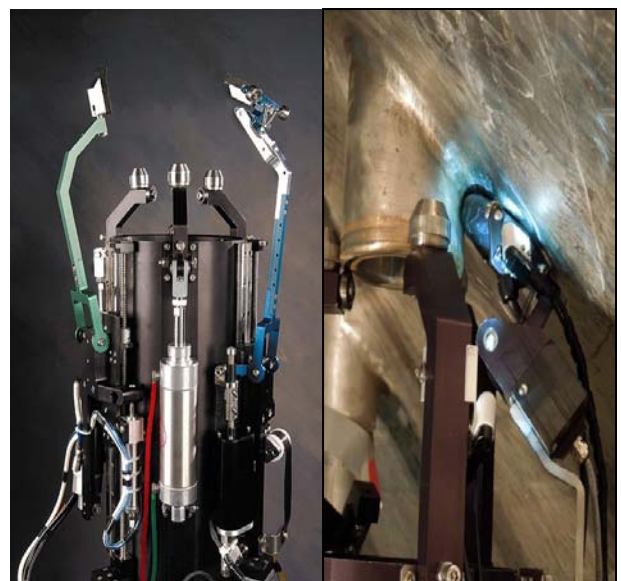


FIG. 10 J-WELD SCANNER WITH TOUCH-POINT FOLLOWER (LEFT) AND CLOSE-UP OF MOUSE-PROBE

vendor capabilities to leverage existing tools to minimize the overall investment.

A complete collection of tools and techniques has been described that encompass the full range of

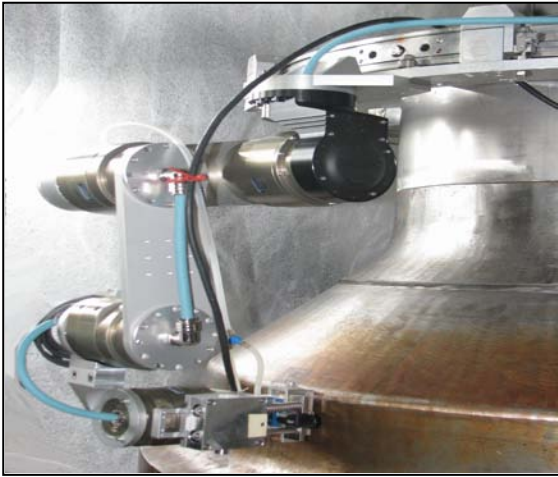


FIG. 11 LIGHT-WEIGHT ROBOTIC ARM REPLACING SPECIFIC TRACK MANIPULATOR FOR HEAD WELDS AND LIGAMENT INSPECTION

current inspection requirements. Developments are continuing to improve capabilities, shorten schedules, minimize dose, and reduce costs.

ACKNOWLEDGMENTS

Manipulators discussed above have been developed by the operational units of AREVA's NDE Solutions group with offices in France, Germany and the US.

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